

Impact of peer interaction on conceptual test performance

Chandralekha Singh

Department of Physics and Astronomy,

University of Pittsburgh, Pittsburgh, Pennsylvania 15260

Abstract

We analyze the effectiveness of working in pairs on the Conceptual Survey of Electricity and Magnetism test in a calculus-based introductory physics course. Students who collaborated with a peer showed significantly larger normalized gain on individual testing than those who did not collaborate. We did not find statistically significant differences between the performance of students who were given an opportunity to formulate their own response before the peer discussions, compared to those who were not. Peer collaboration also shows evidence for co-construction of knowledge. Discussions with individual students show that students themselves value peer interaction. We discuss the effect of pairing students with different individual achievements.

I. INTRODUCTION

Cognitive research suggests that an individual must process new material actively and build proper associations with their prior knowledge for learning to be meaningful. One way to immerse students actively in the learning process is to have them interact with each other. Peer collaboration as a learning tool has been exploited in many instructional settings and with different types and levels of student populations.¹ Although the details vary, students can learn from each other in many different environments.²⁻¹¹

In college physics instruction, Eric Mazur² has popularized a peer instruction method in which the instructor poses several conceptual multiple-choice questions during the lecture. Students discuss their reasoning with peers and are polled about their choices. Mazur has cited several advantages for why this method is effective. Peer interaction keeps students alert during the lectures because they know they must discuss the questions with peers, and it also helps them organize and extend their knowledge. Articulating one's opinion requires attention to logic and organization of thought processes. Instant feedback from students also provides a "reality check" to the instructors about the extent to which students have learned to the concepts. This check can help instructors adjust the pace of the class appropriately. Moreover, there often is a mismatch between instructor and students' expectations of the level of understanding. Peer instruction helps convey instructor's expectations to the students so that students can adjust their expectations. Physics educators also have exploited peer collaboration to teach problem solving using complex context-rich real-life problems,³ to make lecture demonstrations meaningful to students,⁴ and to teach physics without lectures in a workshop style.⁵ An additional advantage of peer collaboration is that it is embedded in a context that can help students retain and recreate the content by remembering the discussion.¹

There have been many more investigations involving the effectiveness of collaboration in K-12 education, both in science and in other disciplines. However, there is little quantitative data from pre-/post-testing (testing before and after group intervention). Most researchers have analyzed the success of peer collaboration based upon patterns of student discussion. According to Vygotsky's socio-cultural perspective,⁶ learning is fundamentally a social process. In this perspective, student learning can be enhanced by participation in various social tasks that are designed by instructors who are familiar with students' prior knowledge. Many

researchers who are influenced by this perspective investigate the role of different types of social environment in mediating and facilitating learning. Rogoff⁷ reviewed the research on collaborative learning in K-12 education. She addressed issues about the success of peer collaboration based on the analysis of individuals and the group as a whole. The analysis of her own research described in her review is not based upon performance on tests given after collaboration, but on the interaction between individuals. She found that children are more likely to examine the logic of arguments with peers than with adults, with more self-generated clarifications of logic and more commentary during discussions with peers. Damon⁸ has contended that peer education has an untapped potential and has advocated peer-based approaches to education. He has claimed that more expert partners may facilitate skill and information learning, while peer partners may facilitate conceptual change or acquisition of new principles. He has asserted that peer collaboration complements rather than supplants adult teaching, freeing up teachers' energy and attention and enabling them to focus on children's other needs. Barron⁹ posed complex multi-step mathematical problem solving to students and discussed how achieving coordination, for example, balanced involvement of both individuals in problem solving, are critical for effective collaboration.

Hogan et al.¹⁰ analyzed the discourse patterns and collaborative scientific reasoning in peer and teacher-guided discussions and discussed their relative advantages. The patterns of verbal interaction within peer and teacher-student scientific sense-making discussions were dissected and the relation between discourse patterns and sophistication of scientific reasoning during discussions was studied. It was found that peers working without a teacher talked more, exhibited a greater level of reasoning complexity, and were better able to justify arguments and synthesize information. The presence of a teacher brought students to a resolution of ideas more efficiently, resulting in a reduced need for talk and reasoning complexity. No data was provided about the learning outcomes or the quality of the students' final models. Azmitia et al.¹¹ found that when friends were grouped together they were more likely to spontaneously justify their solutions, check their answers, and engage in conflicts that were resolved by discussions than groups with members who did not know each other from before.

II. BACKGROUND

In this paper we report on the effectiveness of working in pairs in a calculus-based introductory physics courses. We chose the conceptual multiple-choice test, the Conceptual Survey of Electricity and Magnetism (CSEM),¹² because it is a standardized test that covers a wide variety of qualitative (conceptual) problems that are covered in calculus-based introductory physics courses. Each of the 32 questions on this standardized test has 5 choices (a correct answer and four distracters). Thus, a score significantly better than 20% shows a non-random response. Our investigation supplements previous studies on peer collaboration discussed in the previous section. Students had instruction in the relevant physics principles and concepts before taking the test. Our interest is in exploring the learning gain due to group interactions during qualitative problem solving. In particular, we want to know the extent to which group performance differs from individual performance. We also are interested in understanding the extent to which students can co-construct knowledge,¹ that is, are there instances in which the group members collectively choose the correct response even though each of them had chosen an incorrect response earlier? Also of interest is the extent to which peers retained what they have learned. Are there any differences in learning gains and retention if students are first given an opportunity to think about the problems individually or if a student with a high initial individual score before group intervention is paired with another student with a high or low individual score?

The investigation was performed in four introductory physics courses. Two of these courses formed the experimental group in which group intervention was included, and the other two courses formed the control group with no group intervention. The experimental group consisted of two types of interventions to explore the extent to which giving students an opportunity to formulate their own responses before group intervention (IG protocol) enhanced learning compared to the case where students first worked in groups without a prior opportunity to formulate their own responses (GI protocol). Regardless of the protocol, all students took the CSEM test individually two weeks later after the initial administration of the test to assess the extent to which they had retained the relevant concepts. Each test counted for one quiz.

Some studies show that heterogenous groups are more effective for group learning, while others show that working with friends has special advantages.¹¹ In our study, students were

allowed to choose their own partners. They were encouraged to discuss the questions with each other. Apart from the explicit encouragement by the instructor, students had an additional motivation to discuss the concepts, because the forthcoming examination covered the same material. Moreover, students already had extensive experience working in groups of three in the recitation on context-rich problems³ and in pairs during lecture on Mazur-style concept tests.² We note that the peer collaboration was unguided in that there was no help or facilitation from the instructor except that the physics principles and concepts were covered in earlier classes.

III. DISCUSSION OF DIFFERENT PROTOCOLS

Students in both experimental groups were given the CSEM test twice during a double class period (110 minutes). To obtain two random equivalent samples, all students in the “experimental group” class sitting on one side of the aisle worked individually, followed by group work, while those on the other side of the aisle worked in groups first before working individually. In the IG experimental group, students first worked individually, and then in groups of two. In the GI group (group followed by individual), students first worked in groups of two and then individually. Students worked individually or in a group for 50 minutes. Between the individual and group testing there was a short break, and students were required to turn in their first response so that they could not refer to it when working in pairs (IG) or individually (GI) the second time. The test answers were not discussed with students, so when they switched from individual to group (or vice versa), they did not know if their initial responses were correct.

Each class in the IG protocol had 74 students or 37 pairs (for a total of 148 students). In the GI protocol, one class had 54 students or 27 pairs and another class had 30 students or 15 pairs (total 84 students). As noted, the main motivation for giving the test in both ways was to assess the effect of thinking individually before peer discussion. In Mazur-style peer instruction, students are first asked to think about the concepts individually before talking to peers. Another reason for using both the IG and GI protocols was to evaluate any “test-retest” (also known as “practice” or “carry-over”) effect.

Although the trends in some individual test questions are interesting, we mostly focus here on the effect of group work on overall test scores. Table 1 shows the average indi-

vidual and group scores for the GI and IG protocols. The average performance on the IG and GI protocols are statistically indistinguishable, which suggests that giving students an opportunity to think alone before peer discussion did not improve their group performance significantly. In the IG protocol, the group performance after the individual performance is not a “test-retest” effect. If we consider the protocol samples to be equivalent, we can compare the average performance of the GI protocol (71%) with the average performance in the IG protocol (74%). These two scores are statistically the same. Most of the following discussion focuses on the IG protocol in which it is possible to compare the first individual performance before the group intervention with the second individual performance two weeks after the group intervention.

There are some interesting trends in the time that students took to complete the test during the two successive tests in the IG and GI protocols. In the GI protocol, during the group work only, and in the IG protocol, both during the individual and group work, students roughly took the whole time allotted to them. In contrast, students working individually after the group work in the GI protocol took roughly one third of the time spent on group work. In the IG protocol, despite having worked on the problems individually, it is likely that students were willing to spend time discussing the same test because they found peer collaboration useful. Discussions with individual students support this hypothesis. However, in the GI protocol, after having discussed the test with peers, students were reasonably sure about their answers and did not consider it necessary to reconsider their choices.

A. Evidence for co-construction

Although there is no consensus in the research literature on the definition of “co-construction,”¹ we use the term here to denote cases where neither student alone choose the correct response, but both students as a group choose the correct response. Co-construction can occur for several reasons. For example, if the group members chose incorrect responses, they will have to explain their reasoning to each other. This discussion may reveal flaws in their initial logic, and complementary information provided by their peers can help students converge to the correct solution. Even in cases where both students have the same incorrect response, co-construction can occur if students are unsure about their initial response and are willing to discuss their doubts. Important clues provided by peers during the

discussion can trigger the recall of relevant concepts and can help the group co-construct. One attractive feature of peer collaboration is that because both peers have recently gone through similar difficulties in assimilating and accommodating the new material, they often can relate to each other’s difficulties more easily than the instructor. The instructors’ extensive experience often can make a concept so obvious and automatic that they may not comprehend why students misinterpret various concepts or find them confusing.

Another possible reason for co-construction of knowledge during peer collaboration is related to reduction in the cognitive load.¹³ Cognitive load during problem solving is the amount of mental resources required to solve the problem. Cognitive research suggests that the human “working memory” can keep only seven to nine knowledge pieces (chunks) at a given time during problem solving.¹⁴ Because students’ knowledge structure is more fragmented, their “knowledge chunks” are smaller than that of experts.¹⁴ For example, displacement, velocity and acceleration may constitute three separate “chunks” for a beginning physics student, but they form a single knowledge chunk for an expert in mechanics. The limited processing capacity of the brain makes the cognitive load high during problem solving tasks, leaving few cognitive resources available for learning, extending, and organizing knowledge.¹⁴ The abstract nature of the laws of physics and the chain of reasoning required to draw meaningful inferences makes these cognitive issues critical. According to the theory of distributed cognition, an individual’s cognitive load can be reduced by taking advantage of the environment. Peer collaboration can reduce the cognitive load on each individual because the load is shared by collaborators. Collaborators can take advantage of each other’s strength and the total number of available “chunks” in working memory is larger.¹⁴

Table II displays the percentage of overall cases where neither, one, or both group members chose the correct response individually, and how their choices changed during the group work. Co-construction was observed in 29% of the eligible cases. Table III shows the fraction of responses on each question of the CSEM¹² that went from both incorrect individually to correct group response (001: individual incorrect-individual incorrect-group correct), both incorrect individually to incorrect group response (000), both correct individually to correct group response (111), one correct and one incorrect individually to incorrect group response (100), and one correct and one incorrect individually to correct group response (101). The fraction of responses that went from both correct individually to incorrect group response (110) is negligible. In Table III, an incorrect response is labeled 0 regardless of which incor-

rect choice it was. Table III shows that in some questions, the probability of co-construction was higher than in others.¹² To determine whether students were likely to have chosen an incorrect response as individuals but the correct response as a group due to random guesses, we analyze the first row of Table II in detail. In Table IV, we subdivide this row based on whether both partners had the same or different incorrect responses and if the group response was one of the original incorrect responses or a third incorrect response. Table IV shows that in 25% of the cases where both group members had the same incorrect response, and in 31% of the cases where both had a different incorrect response, the group response was correct. In comparison, the relatively small frequency of a “different” incorrect group response that was not originally selected by either member suggests that students were not merely guessing (see Table IV). For example, in the first row of Table IV there are three other well-designed distracters apart from the one originally chosen by students. If students were randomly guessing, they would have chosen on average the three other distracters (0') with three times the probability than they chose the correct response. On the contrary, only in 8% of the cases in which both students had the same incorrect response, did they chose 0', compared to choosing the correct response in 25% of the cases.

Although we did not conduct formal interviews with students after they worked in groups, we briefly discussed aspects of the group work they found helpful with several students. Most students said that they obtained useful insights about various electricity and magnetism concepts by discussing them with peers. Students frequently noted (often with examples) that they had difficulty interpreting the problems alone, but interpretation became easier with a peer. They also said that talking to peers forced them to think more about the concepts, find fault with their initial reasoning, and remind them of concepts they had difficulty recalling on their own. Qualitative observations show that students were more likely to draw field lines, write equations or sketch drawings in group work than in their individual work.

B. Possible negative impacts of unfacilitated peer collaboration

Negative impacts of unfacilitated peer collaboration in introductory physics are possible. For example, a student with a dominant personality might convince others that his/her logic is correct, even if it is not. Table II (second row) shows that in the cases in which one

individual chose the correct response and the other chose an incorrect response in the IG protocol, 78% of the group responses were correct. The fact that 22% of such cases resulted in an incorrect group response is not very troublesome because it was an unguided peer discussion. It can happen if students who individually chose the correct response are not very confident and cannot defend or justify their response. On most test questions, when one group member individually had the correct response and the other had an incorrect response, the group was very likely to choose the correct response. Individual discussion with some students also suggests that students who chose an incorrect response individually were correspondingly less sure and were more willing to agree with their peer's arguments. The last row of Table II shows that when both students individually answered a question correctly, the group discussion did not result in an incorrect response to within two significant digits. As will be discussed in Sec. IV, group work always resulted in a significantly better average individual gain in comparison to no group work.

IV. INDIVIDUAL GAIN AND RETENTION WITH GROUP INTERVENTION

The individual performances in the GI protocol was superior (70%) compared to the IG protocol (56%). We could hypothesize that students could immediately recall the group responses for all 32 test questions in the GI protocol and their superior performance does not reflect the effectiveness of group work with regard to the retention of the concepts discussed. Similarly, in the IG protocol, the superior group performance compared to the individual performance is due to a large number of cases where the group member with the correct response was able to convince the one with the incorrect response. It does not necessarily imply that students will retain what they learned in the group work. To investigate the impact of group interaction on retention, students took the CSEM test again two weeks after the IG and GI protocols. Although it would have been better to use a different, equally reliable test for assessing similar concepts, none was available.

The average normalized gain g can be defined as $g = \langle (s_f - s_i) / (100 - s_i) \rangle$, where s_i and s_f are the first individual and second individual test scores in percent.¹⁵ All of the gains in the various tables were calculated before rounding the first and second average individual scores to two significant digits. For the students in IG protocol, the average score for the second individual testing was 74% (the same as the average group score earlier), a gain of 0.41

compared to the average initial individual score of 56%. A detailed comparison of the group and second individual test scores shows that about 80% of the overall individual responses chosen by the members of a particular group were the same as the group responses. There are two competing effects: the fact that students forgot some group responses and the fact that they had two weeks to study the questions before the second individual test. Thus, a large fraction of the group responses was retained even after two weeks. We note that students did not know that they would be taking the CSEM test again. The average second individual score for the GI students protocol was 70%. Although this score is lower than the average second individual score for the IG students (74%), the difference is not statistically significant.

A. Effective pairing

To learn about the effect of pairing students with different initial individual scores, we divided the 148 students in the IG protocol into three categories: high (A), middle (B), and low (C), based on their initial individual scores on the CSEM. All students with an initial score $\geq 70\%$ were placed in category A, those with scores less than 70% but greater than 50% were placed in category B and those with scores $\leq 50\%$ were placed in category C. In Tables V and VI we show the initial individual average score and the second individual score in each category for all nine possible pairs. The top rows of Tables V and VI refer to the performance of A students for different kinds of pairings: (A A), (A B) and (A C). Similarly, the middle and bottom rows refer to the performance of B and C students for different kinds of pairings respectively. Table V shows that the initial average scores of the students in the A, B, and C categories regardless with whom they were paired were $\approx 77\%$, 58% , and 40% respectively. Table VI shows that the second individual average scores of the students in the A, B, and C categories regardless with whom they were paired were $\approx 86\%$, 75% , and 64% respectively. In comparison, for all 148 students together, the initial individual average score was 56%, the average individual gain was 0.41, and the second individual average score was 74%. The difference in the normalized gain in different categories in the matrix is not statistically significant.

V. COMPARISON WITH STUDENTS WITHOUT GROUP INTERVENTION

To gauge the effectiveness of group work on individual performance, we employed a control group in which 178 students from two different calculus-based introductory physics courses took the CSEM test once individually (average score 57%) and then again two weeks later without any group intervention (average score 63%). The normalized gain for the control group is 0.14, which is much less than the gain of 0.41 for students in the IG protocol who worked in pairs before the individual testing two weeks later. Table VII shows the average first (I) individual score, the second (II) individual score, and the normalized gain g for the control students divided into the same A, B, and C categories according to their first individual score and for all students. Table VII shows that the performance of the control group in none of the categories was much improved two weeks later. A comparison of Tables VI and VII shows that in each category students in the IG protocol obtained roughly 10 points higher on the second individual testing than those in the control group.

VI. SUMMARY

We have investigated the effectiveness of working in pairs without facilitation from the instructor on the CSEM test in a calculus-based introductory physics course. Students who worked with peers showed significantly higher normalized gain on subsequent individual testing than a control group that took the test individually twice. In our limited sample, we did not find any statistical difference between the performance of students in the IG and GI protocols.

The peer collaboration also shows evidence for co-construction. Students who individually chose an incorrect response were able to find the correct response working as a group with a frequency that is roughly ten times higher than that predicted by random guessing. Co-construction also happened in cases where the individual incorrect responses were the same. Discussions with individual students show that discussing their doubts with each other helped them. Peer collaboration provided students an opportunity to articulate their own thoughts and make sense of their peer's thought processes. This process made students critical of their own thinking. Discussions with individual students indicated that they value peer interaction. Also, students who had worked on the test individually, when asked

to work with peers immediately following the individual work, used the entire time allotted to them (in contrast to the group that first worked with peers and then individually). We found no significant differences between individual gains regardless of whether a student with a high individual score was paired with another student who had a high or a low individual score.

Because unfacilitated peer collaboration requires a minimal effort on the part of instructors, students should be given ample opportunity and incentive to collaborate with peers both inside and outside of the classroom. There are several factors that seem to be important for optimizing the benefits of peer collaboration. A time constraint, even for the collaborative work done outside of the classroom (for example, a time frame within which the work should be submitted) may be helpful for keeping students focussed. A reward system (for example, a small amount of homework, quiz, or bonus points), and an incentive for individual accountability (for example, future examination in which students will work alone on similar concepts) is helpful for getting the most out of collaborative work.

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¹ P. Dillenbourg, “What do you mean by collaborative learning?,” in *Collaborative Learning: Cognitive and Computational Approaches*, edited by P. Dillenbourg (Pergamon Press, Oxford, 1999), pp. 1–19; E. Alexopoulou and R. Driver, “Small-group discussion in physics: Peer interaction modes in pairs and fours,” *J. Res. Sci. Teach.* **33**, 1099–1114 (1996); A. King, A. Staffieri, and A. Adelgais, “Mutual peer tutoring: Effects of structuring tutorial interaction to scaffold peer learning,” *J. Educ. Psych.* **90**, 134–152 (1998); D. W. Johnson, R. T. Johnson, M. B. Stanne, “Impact of goal and resource interdependence on problem-solving success,” *J. Social. Psych.* **129** (5), 621–629 (1989); C. Kneser and R. Ploetzner, “Collaboration on the basis of complementary domain knowledge: Observed dialogue structures and their relation to learning

- success,” *Learning and Instruction* **11**, 53–83 (2001); A. T. Lumpe and J. R. Staver, “Peer collaboration and concept development: Learning about photosynthesis,” *J. Res. Sci. Teach.* **32**, 71–98 (1995).
- ² E. Mazur, *Peer Induction: A User’s Manual* (Prentice Hall, Upper Saddle River, NJ, 1997); C. H. Crouch and E. Mazur, “Peer Instruction: Ten years of experience and results,” *Am. J. Phys.* **69** (9), 970–977 (2001).
- ³ P. Heller, R. Keith, and S. Anderson, “Teaching problem solving through cooperative grouping. Part I: Group versus individual problem solving,” *Am. J. Phys.* **60**, 627–636 (1992); P. Heller and M. Hollabaugh, “Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups,” *Am. J. Phys.* **60**, 637–644 (1992).
- ⁴ D. R. Sokoloff, and R. K. Thornton, “Using interactive lecture demonstrations to create an active learning environment,” *Phys. Teach.* **35**, 340–347 (1998); C. Singh, “Exploration center for large introductory physics courses,” *Phys. Teach.* **38**, 189–190 (2000).
- ⁵ P. W. Laws, “Millikan Lecture 1996: Promoting active learning based on physics education research in introductory physics courses,” *Am. J. Phys.* **65**, 14–21 (1997).
- ⁶ L. Vygotsky, *Mind in Society: The Development of Higher Psychological Processes* (Harvard University Press, 1978); J. Wertsch, *Mind in Action* (Oxford University Press, NY, 1998).
- ⁷ B. Rogoff, “Cognition as a collaborative process,” in *Cognition, Perception and Language*, edited by D. Kuhn and R. Siegler (Wiley, NY, 1998), Vol. 2, pp 679–743.
- ⁸ W. Damon, “Peer education: The untapped potential,” *J. Appl. Devel. Psych.* **5**, 331–343 (1984).
- ⁹ B. Barron, “Achieving coordination in collaborative problem-solving group,” *J. Learning Sci.* **9** (4), 403–436 (2000).
- ¹⁰ K. Hogan, B. Nastasi, and M. Pressley, “Discourse patterns and collaborative scientific reasoning in peer and teacher-guided discussions,” *Cognition and Instruction* **17** (4), 379–432 (2000).
- ¹¹ M. Azmitia and R. Montgomery, “Friendship, transactive dialogues and the development of scientific reasoning,” *Social Devel.* **2** (3), 202–221 (1993).
- ¹² D. P. Maloney, T. L. O’Kuma, C. J. Hieggelke, and A. V. Heuvelen, “Surveying students’ conceptual knowledge of electricity and magnetism,” *Am. J. Phys.* **69**, S12–S23 (2001).
- ¹³ J. Sweller, “Cognitive load during problem solving: Effects on learning,” *Cognitive Science* **12**, 257–285 (1988); J. Sweller, R. Mawer, and M. Ward, “Development of expertise in mathematical

problem solving,” J. Exptl. Psychology: General **112**, 639–661 (1983).

¹⁴ H. Simon, *Reason in Human Affairs* (Basil Blackwell, 1983); H. Simon, “Rational choice and the structure of the environment,” H. Simon, Psych. Rev. **63**, 129–138 (1956).

¹⁵ R. Hake, “Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses,” Am. J. Phys. **66**, 64–74 (1998).

Tables

Protocol	I	G
GI	70%	71%
IG	56%	74%

TABLE I: The average individual (I) and group (G) scores for the GI and IG protocols. There were 148 students in the IG protocol and 84 students in the GI protocol.

Individual Response		Group Response	
		Incorrect	Correct
neither correct	24%	71%	29%
one correct	40%	22%	78% s
both correct	36%	0%	100%

TABLE II: Distribution of the average group response for various combinations of individual responses of group members in the IG protocol. The second column displays the percentage of the overall cases where neither, one, or both group members had the correct response individually.

Question #	001	000	111	100	101
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00
28	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00
31	0.00	0.00	0.00	0.00	0.00
32	0.00	0.00	0.00	0.00	0.00
33	0.00	0.00	0.00	0.00	0.00
34	0.00	0.00	0.00	0.00	0.00
35	0.00	0.00	0.00	0.00	0.00
36	0.00	0.00	0.00	0.00	0.00
37	0.00	0.00	0.00	0.00	0.00
38	0.00	0.00	0.00	0.00	0.00
39	0.00	0.00	0.00	0.00	0.00
40	0.00	0.00	0.00	0.00	0.00
41	0.00	0.00	0.00	0.00	0.00
42	0.00	0.00	0.00	0.00	0.00
43	0.00	0.00	0.00	0.00	0.00
44	0.00	0.00	0.00	0.00	0.00
45	0.00	0.00	0.00	0.00	0.00
46	0.00	0.00	0.00	0.00	0.00
47	0.00	0.00	0.00	0.00	0.00
48	0.00	0.00	0.00	0.00	0.00
49	0.00	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00	0.00
51	0.00	0.00	0.00	0.00	0.00
52	0.00	0.00	0.00	0.00	0.00
53	0.00	0.00	0.00	0.00	0.00
54	0.00	0.00	0.00	0.00	0.00
55	0.00	0.00	0.00	0.00	0.00
56	0.00	0.00	0.00	0.00	0.00
57	0.00	0.00	0.00	0.00	0.00
58	0.00	0.00	0.00	0.00	0.00
59	0.00	0.00	0.00	0.00	0.00
60	0.00	0.00	0.00	0.00	0.00
61	0.00	0.00	0.00	0.00	0.00
62	0.00	0.00	0.00	0.00	0.00
63	0.00	0.00	0.00	0.00	0.00
64	0.00	0.00	0.00	0.00	0.00
65	0.00	0.00	0.00	0.00	0.00
66	0.00	0.00	0.00	0.00	0.00
67	0.00	0.00	0.00	0.00	0.00
68	0.00	0.00	0.00	0.00	0.00
69	0.00	0.00	0.00	0.00	0.00
70	0.00	0.00	0.00	0.00	0.00
71	0.00	0.00	0.00	0.00	0.00
72	0.00	0.00	0.00	0.00	0.00
73	0.00	0.00	0.00	0.00	0.00
74	0.00	0.00	0.00	0.00	0.00
75	0.00	0.00	0.00	0.00	0.00
76	0.00	0.00	0.00	0.00	0.00
77	0.00	0.00	0.00	0.00	0.00
78	0.00	0.00	0.00	0.00	0.00
79	0.00	0.00	0.00	0.00	0.00
80	0.00	0.00	0.00	0.00	0.00
81	0.00	0.00	0.00	0.00	0.00
82	0.00	0.00	0.00	0.00	0.00
83	0.00	0.00	0.00	0.00	0.00
84	0.00	0.00	0.00	0.00	0.00
85	0.00	0.00	0.00	0.00	0.00
86	0.00	0.00	0.00	0.00	0.00
87	0.00	0.00	0.00	0.00	0.00
88	0.00	0.00	0.00	0.00	0.00
89	0.00	0.00	0.00	0.00	0.00
90	0.00	0.00	0.00	0.00	0.00
91	0.00	0.00	0.00	0.00	0.00
92	0.00	0.00	0.00	0.00	0.00
93	0.00	0.00	0.00	0.00	0.00
94	0.00	0.00	0.00	0.00	0.00
95	0.00	0.00	0.00	0.00	0.00
96	0.00	0.00	0.00	0.00	0.00
97	0.00	0.00	0.00	0.00	0.00
98	0.00	0.00	0.00	0.00	0.00
99	0.00	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00	0.00

TABLE III: In the IG protocol, the fraction of responses on each question that went from both incorrect individually to correct group response (001), both incorrect individually to incorrect group response (000), both correct individually to correct group response (111), one correct and one incorrect individually to incorrect group response (100) and one correct and one incorrect individually to correct group response (101). Instances where both correct individually went to incorrect group response (110) were negligible.

both individual responses were incorrect	Group Response		
	1	0	0'
same incorrect (41%)	25%	67%	8%
different incorrect (59%)	31%	55%	14%

TABLE IV: Distribution of the average group response for cases where both members had the same or different incorrect individual response in the IGI protocol. 1, 0 and 0' refer to “correct,” “one of the original incorrect” and “an incorrect choice not originally selected by either student” group response respectively.

(a)	pairing		
	A	B	C
A	78	77	75
B	58	59	58
C	43	39	39

TABLE V: The average initial individual score in percent. The top row refers to the performance of A students for different kinds of pairings: (A A), (A B) and (A C). Similarly, the middle and bottom rows refer to the performance of B and C students, respectively. There were a total of 148 students out of which 12 chose AA pairing, 12 chose BB pairing, 24 chose CC pairing, 36 chose AB pairing, 20 chose AC pairing and 44 chose AC pairing.

	pairing		
	A	B	C
A	88	86	85
B	79	71	75
C	64	65	62

TABLE VI: The average second individual test score in percent for the nine types of pairs in the IG protocol

Student Type	I	II	g
A	73	77	0.14
B	58	65	0.17
C	42	49	0.12
All	57	63	0.14

TABLE VII: The percent average first (I) individual score, the second (II) individual score two weeks later, and the normalized gain g for the 178 control students (no group intervention) divided in high (A), middle (B) and low (C) categories according to their first individual score and for all students. There were 56 students in category A , 54 in category B and 68 in category C . The gains were calculated before rounding the initial and second average individual scores to two significant digits.